

Indicator based sustainability assessment tool for affordable housing construction technologies

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ABSTRACT

With the growing worldwide demand for affordable housing and the importance of supporting and stimulating sustainable development, the need for sustainable solutions in the affordable housing sector is at a peak. The present paper screened about 75 construction technologies and assessed 46 of them. The present paper presents the first results of a step wise approach to identify, assess and recommend most promising technologies for affordable housing projects. A database was developed to store detailed technical information about each of the technologies. A grading and ranking scheme was developed to identify the most promising construction technologies from a sustainability perspective. The main challenges for affordable housing production and most relevant assessment indicators were identified from the literature, interviews and meetings with experts. An indicator based assessment system was developed by cross-referencing the identified eight challenges with ten selected indicators. The final ranking demonstrated that a wide variety of technologies perform strongly overall, and these range from bio-based materials, such as bamboo and timber, to industrialized technologies, such as concrete. Moreover, the possibilities for improvement are vast, and the option of combining different technologies seems to be the most promising approach.

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1. Introduction

Housing is one of the most basic human needs and is a key component in the sustainable development of a community (Dumreicher and Kolb, 2008). In general, sustainable development is divided into three interacting sectors: economic, environmental, and social (Keiner, 2005). From a social perspective, housing not only offers shelter but also gives a sense of a secure future and strengthens local communities (Arman et al., 2009). On the other hand, the housing sector is responsible for a great deal of greenhouse gas emissions, energy and material use, waste production, and changes in land-use dynamics (U.E. UN Habitat, 2008). Finally, from an economic perspective, houses are among the major investments that people make in their lifetimes (Maliene and Malys, 2009), and the housing sector is related to 10% of the global gross domestic product and 7% of global jobs (UN Habitat, 2009).

The worldwide demand for affordable housing has grown in recent decades and is expected to continue to grow (Wood, 2007). Moreover, the affordable housing sector has been regarded as one of the less penetrated markets by private companies (World Bank,

2006). Thus, the affordable housing sector provides a wide range of opportunities for development along with a series of challenges to be overcome (Wherever, 2008). Several challenges to affordable housing have been put forth in the literature. The following eight are highlighted as key challenges: scarcity of resources; lack of sufficient funds; shortage due to urgency of demand; shortage of skilled labour; quality control; wastage due to inefficiency; lack of added value creation; and quality and location.

Due to the inherent complexity of the affordable housing problem, it was proposed to have a step wise approach. The first step, from which this paper presents the results, comprehends three parts, first a global screening of construction technologies used in affordable housing programs; second the development of an indicator based assessment system; and third a technology's assessment and ranking. Further steps will consider the development of life cycle assessments for most promising technologies, considering local factors. The final step will be a final selection process, carried out with specific communities and organizations interested in developing affordable and sustainable housing projects, to finalize with its implementation in form of a pilot project. Therefore, the goal of this paper is to identify construction technologies that will be able to sustainably provide shelter to low and lowest income communities in urban areas of emerging economies countries. To identify these technologies an indicator based assessment system was developed. The indicators can be clustered into the three main categories identified by the World Commission

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on Environment and Development: Economic, Environmental and Societal (W.C.o.E.a.D., 1987). The highest-ranking technologies are presented and studied in detail in Section 6 of this paper.

1.1. The definition of affordable housing

The concept of affordable housing is diverse and complex but can be generally described in economic terms (Wherever, 2008). An affordable house can be defined as a house that a family group can acquire within a given period, which generally ranges from 15 to 30 years. This period is directly connected to the acquisition capacity of the group and the financial support that they can obtain in terms of loans, credits and subsidies (UN Habitat, 2009). Because an affordable house is such a long-term investment, it should provide added value to its owners in terms of comfort, quality and lifespan (Jenkins et al., 2007). In this sense, affordable housing, as discussed in this paper, is different from the concept of relief shelter and considers the social effects of long-term habitation. Affordable housing is defined in this paper as housing that costs less than 200 USD/m² to produce, including the costs associated with construction and finishing details.

1.2. The need for sustainable affordable housing

When analysing global development scenarios, the building sector is obviously of high social and economic importance in developing and the least-developed countries. The tendency towards urbanization in these countries is well documented, and it is expected that 70% of the world's population will be living in cities by 2050 (World Bank, 2006). This trend is primarily driven by the perception of cities as centres of wealth and prosperity that attract people from rural areas in search of better futures (Dumreicher and Kolb, 2008).

This increase in the global urban population will inevitably result in a very sharp increase in the demand for housing. Unfortunately, the current housing sector cannot cope with the demand for living space (Jenkins et al., 2007). This gap between demand and supply creates a very complex problem, driving the housing sector towards less efficient and more-expensive solutions and new city dwellers towards informal (and often illegal) independent construction of dwellings (Arman et al., 2009). Independent construction has become a widespread phenomenon in emerging economy countries. It has driven a corresponding sense of urgency to develop socially responsible housing solutions (Erguden, 2001) that do not unnecessarily impact the environment and that can be acquired by low-income family groups in a reasonable period.

The building sector is regarded by many authors as the primary consumer of resources and energy in the modern environment (Kavgic et al., 2010). Therefore, it is of great importance to develop technologies to reduce negative environmental impacts and to assess (Ali and Al Nsairat, 2009) the potential and performance of traditional and novel ideas. Furthermore, the development of sustainable housing projects should aim to reduce the energy and material flows in their whole life cycle, starting on its planning and design phases, considering their construction and use and their final renovation or demolition (Arslan, 2007). To identify the best solution, a consistent set of indicators must be developed (Yao, 2005) that encompass all the aspects of sustainability. Furthermore, the assessment of sustainable construction technologies and solutions requires the development of comparison schemes and benchmarks that will highlight the challenges and opportunities (Monahan and Powell, 2011) of each technology.

1.3. Key challenges of affordable housing

The development of affordable housing project as is in itself a very complex challenge. The first step in the technologies

assessment process was to identify, which are the main challenges for the execution of such projects. These challenges were identified on the literature and through interviews with organizations like UN habitat, HILTI Foundation and UNESCAP. The proposed challenges do not claim to show the whole variety of difficulties that can occur when providing newly constructed affordable houses but to highlight the most commonly occurring. The identified challenges were used to configure a matrix that relates the main challenges with the proposed indicators. The challenges are described on the following sections.

1.3.1. Scarcity of resources

The consumption of resources increases tremendously by the rapid urban growth and changing living standards in emerging economies. Already today shrinking resources and upcoming scarcities are a main issue. In case of the housing deficit this challenge means to look favourably upon the improvement of existing methods and the establishment of innovative technologies acting as drivers for higher efficiency or resource substitution. Financial and technical capabilities of municipalities have to be strengthened and private sector has to serve all income groups. From the construction point of view this means: producing good quality construction materials, increasing its efficiency and reducing its embodied energy.

1.3.2. Lack of sufficient funds

The income of households in vulnerable conditions and/or informal settlements is usually one of the lowest on given countries. The marginal income of the target group has to be considered as a key limitation when thinking about construction technologies. Even though this project intends to highlight technologies that are able to produce sound results over the whole life cycle, the initial construction costs are a key driver for the implementation of a concept for this market segment. Being cost efficient is therefore assessed as key challenge for all technologies presented in this research. As the income is typically not only low but also irregular, the credibility of the dwellers is predominantly insufficient for the loan taking procedure in conventional credit institutes.

1.3.3. Time shortage due to urgency of demand

The rapid urban growth asks for fast solutions however the huge housing demand requires large volumes to be managed. Bureaucratic and legal burdens frequently lead to longer time spans than needed. A clear lack of effective implementation strategies is a major challenge that has to be tackled by the improvement of the interface between policy instruments and reality. A lot has been done in policy framework but its implementations is still lacking behind.

1.3.4. Shortage of skilled labour

One important role of housing production is the generation of new jobs, particularly for unskilled labour. Thus, technologies that require a high skill level will face significant problem in finding skilled and trained works among the members of the target communities. Thus, technologies that require the lowest level of both skill and training will have priority.

1.3.5. Quality control

Beside the significantly difficult access to finance funds, the quality of the final products is one of the most relevant challenges. It does not only affect the performance of the house but also its technical useful life. Thus, is of great relevance to control and assure the quality of materials, and end products as well as the proper utilization on site.

1.3.6. Wastage due to inefficiency

The wastage of resources due to inefficient processes or tools causes an increase in investment costs of around 12%. But beyond the negative influence on costs, wastage also causes negative impacts on resource consumption. A shift from in situ construction to prefabrication and a higher standardization of work flows probably result in less quality problems and lower wastage of resources.

1.3.7. Lack of added value creation

In regard of the inadequate living conditions the dwellers lived in before, it is important to contribute positively to the development of the local environment. The target population is usually embossed by political and social exclusion. One key principle is to engage locals during planning and construction, another is to rely on locally available materials.

1.3.8. Quality and location

Low quality products reduce the houses' life spans and increase the need for maintenance interventions. As mentioned in the book "House of Form and Culture" the cultural, social and economic norms of the specific societies must be reflected in shelter and settlement responses (Rapoport, 1969). A second principle is that strategic planning covering land use, tenure, livelihoods and services have to be integrated in the method in addition to shelter construction. Otherwise there is a danger that solutions do not become permanent value.

1.4. Indicator selection

One of the biggest challenges for this research was select a set of indicators that would encompass the previously described challenges. Based on previous experiences, it was decided to start the whole process by a clear definition of an indicator. The most appealing definition was presented by Heink and Kowarik (2010) describing the indicator as a measure from which conclusions on the phenomenon of interest can be inferred. Moreover, as proposed by Moldan et al. (2011) the main challenges of an indicator system will relate to its use and interpretation. To minimize the impact of this challenge a linear grading scale was applied for each indicator. This process brings on its self, new challenges by reducing the sensitivity between values, making it more difficult to rank technologies that will end up with equal scores. On the other hand, a linear grading scale reduces the subjectivity on the assessment process.

Another complexity was added by the enormous amount of indicators and indicators set extensively described in the literature. Most of these sets are focused on specific aspects of sustainability or simply focus on technical components. As proposed by Jian-yi et al. (2012) the main challenges was not the lack of indicators but the lack of a clear process selecting them selecting indicators, and linking them to the final objective of assessing the technologies' sustainability performance. Therefore, the indicators were selected based not only on its recurrent use in affordable housing projects but also because of its connection to the program's success. Moreover, the great majority of these indicators are connected with affordable housing programs that hand been built around the world. Moreover, as proposed by Krank and Wallbaum (2011), the weaknesses and strengths of each program was studied in relation with its indicators system, in order to provide the background for the final set of indicators used on the present research. The selection of indicators were further refined with the help of experts from organizations like the HILTI foundation and UN ESCAP. The final selection of indicators; a brief description; and its grading scale are presented on the following section.

2. Methodology

In this paper, the methodology for screening and rating sustainable housing technologies consisted of three primary steps: data collection, data processing, and technology screening.

2.1. Data collection procedures

Motivated by the diversity of building technologies and the absence of a common exchange platform, the aim was to develop a database with a wide range of data sources. Three major data sources consulted were: international development organizations; the private sector; and research institutions.

Data for the present research was collected from the published literature about existing technologies and concepts; the databases of organizations involved in affordable housing projects; and personal interviews with representatives of the companies producing affordable housing technologies.

A format using the 18 levels of information shown in Table 1 was developed to standardize the collected data. This format enables the systematic study of different technologies and formed the basis for the grading and ranking process.

2.2. Data processing

The total sample encompasses approximately 75 building technologies, from which 46 were selected for the assessment. A database was developed with 2–4 pages of information for each technology. The first pre-requisite on the screening process was an economic filter that excluded any technologies with initial construction costs above 200 USD/m² from further study.

2.3. Technology assessment

The indicators for assessing the construction technologies are based on the key challenges identified in the first section of this paper. Furthermore, through in depth study of affordable housing programs, as explained in Section 1.4 and interviews with experts, from organizations working on the development of affordable housing programs, the ten most commonly used and accepted indicators were selected. The concept of sustainability was based on widely accepted definition, developed by the Brundtland Commission in 1987, that is: "to meet the needs of the present generation without compromising the ability of future generations to meet their own needs" (W.C.o.E.a.D., 1987). Based on this definition and the present research used a triple-bottom-line approach that

Table 1
Database' information categories.

1	Name of the technology
2	Information source, country of practice and reference projects (if available)
3	Pictures
4	Building category
5	Size dimension
6	Settlement environment
7	Construction components
8	Cost per m ²
9	Building process
10	Time schedule
11	Economy of scale mass production
12	Durability
13	Maintenance requirements
14	Modularization flexibility
15	Potential for recycling demolition
16	Local value creation
17	Social acceptance
18	Interface to basic services

considers the economic, ecological and social aspects of each technology. It is important to remark that most of the selected indicators are measures of dimensions of economic, social or environmental unsustainability which must be minimized to keep on a sustainable trajectory. And as described by Lyon, they are guides to management future decision and action, but they cannot guarantee sustainability (Dahl, 2011). Furthermore, this approach allows the rankings of indicators that can help identify the weaknesses and strengths of technologies through a sensitivity analysis. In the following sections, the assessment indicators are briefly described, and a table is presented that contains the values used to grade each technology.

2.3.1. Initial construction costs per m²

The initial construction costs are a key determinant of the successful implementation of a technology on the market. This indicator addresses the key challenge “lack of sufficient funds”. The amount listed under [USD/m²] in the ranking matrix includes all direct and indirect costs of the superstructure including standard equipment, such as windows, doors, inner walls and kitchen/sanitation facilities. Furthermore, labour costs for construction are included. When only the total project cost was given, a scientific estimate of the margin was made using a ratio work cost to material cost of 20:80. This ratio was based on the literature (Bhaskara, 1994; Mathur, 1993) and discussion with experts from the Hilti foundation (Bürmann, 2010) working on this field. The proposed ratio considers that most of the studied technologies are meant to produce single family housing units; to use limited unskilled labour (mainly future inhabitants); and to maximize the initial investment. The price of land and infrastructure costs for water, sewage, roads and electricity are not included in the initial construction costs of the ranking matrix. It should be noted that the initials costs refer to the value provided by the company referred in the fact sheet. Labour and material costs might vary according to country, and this must be taken into account when considering transferring technologies (see Table 2).

Table 2
Indicator values – initial construction costs.

Initial construction costs [USD/m ²]	Rating
<40 USD	10
<60 USD	8
<100 USD	6
<140 USD	4
>180 USD	2
N/A	0

2.3.2. Requirements of the production and construction processes

Housing construction can create a significant number of jobs. It is important to define the skill level associated with these jobs. This indicator focuses on skill and equipment requirements in the development, production, and construction phases. This indicator tackles the key challenge “shortage of skilled labour” by reducing the rating of technologies that require high skill levels (see Table 3).

Table 3
Indicator values – requirement of the production and construction processes.

Requirements production construction process	Rating
Unskilled labour with no training or local skills traditionally available, low-tech tools	10
Unskilled labour with short training (<2 weeks) or local skills available	8
Unskilled labour with intensive training (several weeks) or skilled workers	6
Advanced skills or tools required	4
Very advanced skill level or tools required	2
Information not available	0

Table 4
Indicator values – time schedule, degree of prefabrication.

Time schedule, prefabrication degree	Rating
Erection of one unit <1 day	10
Erection of one unit 1–3 days	8
Erection of one unit <1 week	6
Erection of one unit <2 weeks	4
Erection of one unit >2 weeks	2
Information not available	0

2.3.3. Time schedule, prefabrication degree

This indicator evaluates the importance of prefabrication, supply chains, and management, each of which are indirectly linked to the costs (see Table 4).

2.3.4. Economy of scale, prefabrication degree

The scalability of the technology plays an important role on this indicator, as it is indirectly linked to the initial construction costs. As the demand for houses grows, programs that utilize economies of scale have significant potential to reduce costs through mass production (see Table 5).

Table 5
Indicator values – economy of scale, mass production.

<i>Economy of scale, mass production</i>	
Immense price reduction potential	10
Significant large price reduction potential or only possible with large scale approach	8
Decisive price reduction potential through mass production or large scale approach of advantage	6
Minor price reduction potential through mass production	4
No significant price reduction potential through mass production	2
Information not available	0

2.3.5. Durability

The service lifespan of the house plays a major role in the creation of local value as well as in resource consumption. Good indicators to assess the durability of building technology include resistance against insects and against natural deterioration, such as high humidity, earthquakes, flooding and wind loads (see Table 6).

Table 6
Indicator values – durability.

<i>Durability</i>	
>40 years	10
>30 years	8
>20 years	6
>10 years	4
<10 years	2
Information not available	0

2.3.6. Maintenance requirements

The integration of maintenance requirements is relevant when taking a holistic view of a building's life cycle. Costs (as well as resources) can be saved by reducing maintenance requirements. This key indicator complements the initial construction costs by accounting for the maintenance requirements over a building's life-cycle (see Table 7).

Table 7
Indicator values – maintenance costs.

<i>Maintenance costs – interaction costs for corrective and preventive maintenance</i>	
Seldom interventions	10
Interventions of low skill and cost level	8
Average interventions of medium skill and cost level	6
Very frequent interventions	4
Intervention of advanced skill and cost level	2
Information not available	0

2.3.7. Modularization and flexibility

This indicator captures a technology's capacity to be delivered in ready-engineered modules and kits as well as its flexibility to floor plan changes. Housing design needs to be flexible to adapt to the different needs of each location and cultures. This mainly aiming at a future the expansion of a building unit to better satisfy the family unit's space needs (see Table 8).

Table 8

Indicator values – modularization and flexibility.

<i>Modularization and flexibility</i>	
High flexibility in case of change of use	10
High modularization	8
Medium modularization or medium flexibility in case of change of use	6
Low modularization	4
Low flexibility in case of change of use	2
Information not available	0

2.3.8. Local value creation

This indicator evaluates integrated design features that include communities on both design and production process of socially accepted architecture. Moreover, housing schemes that fulfil mixed functions and provide broad socio-economic to the locals are preferred (see Table 9).

Table 9

Indicator values – local value creation.

<i>Local value creation B material availability</i>	
Available in the country own open market with high potential for large scale use	10
Available in the country own open market with medium potential for large scale use	8
Available in the country potential market (not currently commercial)	6
Large degree of import	4
Not available on the local market	2
Information not available	0

2.3.9. Interface to basic utilities

This indicator accounts for how each specific technology can be connected with existing infrastructure such as drinking water, sewage, waste disposal and housing amenities (e.g. ventilation, lighting, heating, and energy) (see Table 10).

Table 10

Indicator values – interface to basic services.

<i>Intersection to infrastructure and housing techniques</i>	
Integrated within construction process, reduced efforts	10
Minimal effort for integration	8
Additional processes required such as wall chasing	6
Large effort for integration	4
Only exposed possible	2
Information not available	0

2.3.10. Recycling and demolition ability

This indicator considers the potential and required effort for demolishing and recycling the main construction components of a building (see Table 11).

Table 11

Indicator values – recycling and demolition ability.

<i>Recycling and demolition ability</i>	
High degree of recycling	10
Low demolition effort	8
Medium degree of recycling and demolition effort	6
High demolition effort	4
Low degree of recycling	2
Information not available	0

Table 12
Overview key challenges and assessment criteria.

Key challenges	Cost per m ² (superstructure only)	Requirements building process, skills	Time schedule, prefabrication degree	Economy of scale, mass production	Modularization and flexibility	Durability	Maintenance needs	Recycling potential, demolition ability	Local value creation – labour, material	Interface infrastructure and housing techniques
Scarcity of resources				x	x			x	x	
Lack of sufficient funds				x	Has to be tackled by a business model				x	x
Shortage due to urgency of demand	x		x		x		x			x
Shortage of skilled labour		x	x							x
Quality control		x	x	x						x
Wastage due to inefficiency		x	x							
Lack of added value creation					x			x	x	
Quality and location		x		x	x		x			

2.4. Overview challenges and indicators

Table 12 presents how the identified challenges relate to the proposed indicators. It can be observed that many indicators are able to assess the ability of a building technology in

more than one key challenge. This shows on one hand that the proposed set of indicators covers the whole spectre of challenges for affordable housing and in the other hand indicates that the set can still be refined without losing sensitivity on its assessment.

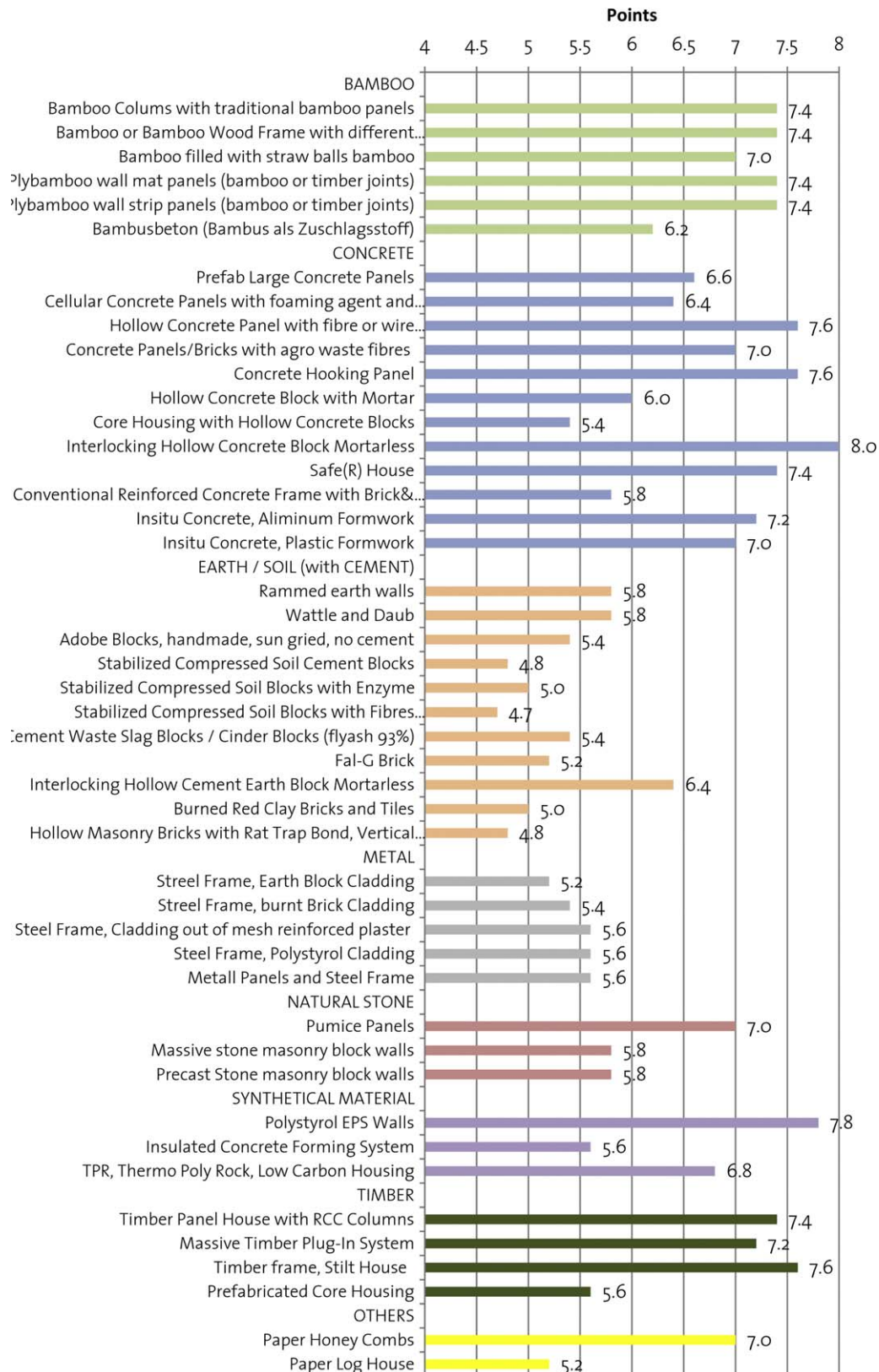


Fig. 1. Sustainability assessment of construction technologies.

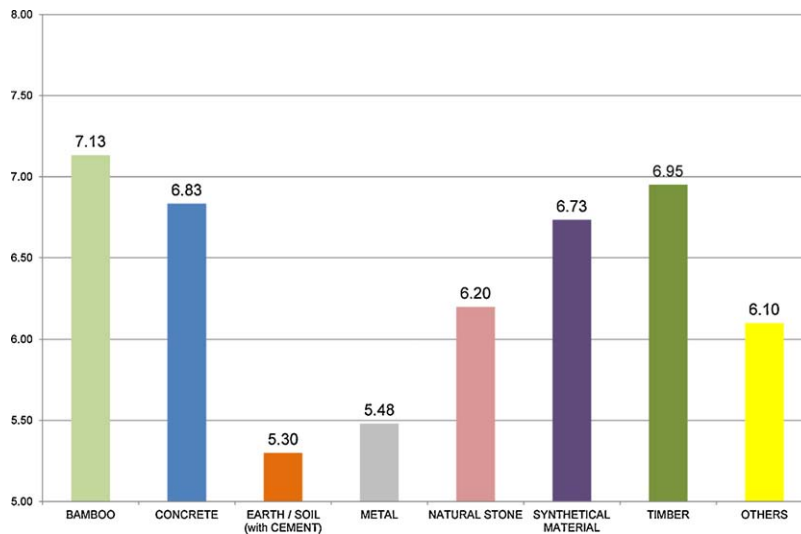


Fig. 2. Average per construction technology category.

3. Results

The final screening showed that the data had standard deviations of 0.98 showing that the results are very compact and distributed over a relatively short range. Fig. 1 shows that there is no perfectly ranked technology under the proposed set of indicators. Only a few technologies were even ranked at the top of three categories. These results demonstrate that the studied technologies each have specific strengths. Many of them can be considered promising depending on the emphasis of a particular housing project. The final ranking also shows that the best-performing technologies overall are not the best technologies in each category but rather are those technologies that obtained average and above-average results in each category.

3.1. Average per material's group

Fig. 2 presents the results of the assessment aggregated by category. This approach helps to identify promising technologies in a

general level and not simply identify individual over performing cases, which can be only applied on specific contexts. From graphs 2 it is clear that bio based technologies have the highest scores followed by industrialized products as concrete and synthetically materials. While the categories metal and earth/soil obtained the lowest marks.

3.2. Average per assessment indicator

Fig. 3 presents the average results studied per indicator. These results show that the studied sample of technologies perform very well in terms of local added value creation; its recycling ability and the skills requirements. On the other hand, it is clear that there is significant room for improvement in relevant indicators such as cost per square meter, economy of scale and durability among others. Furthermore, more research and efforts should be allocated to further develop technology's performance on the low scoring indicators.

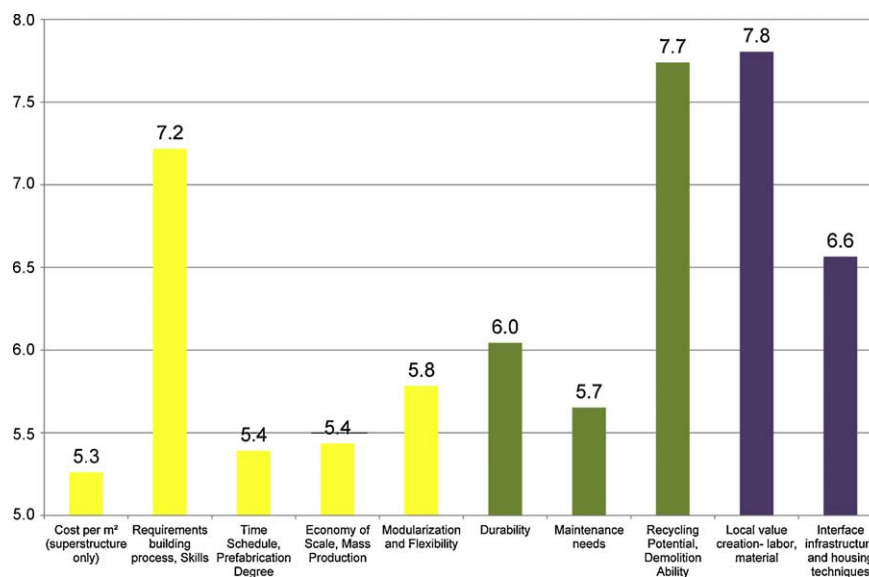


Fig. 3. Average per assessment indicator.

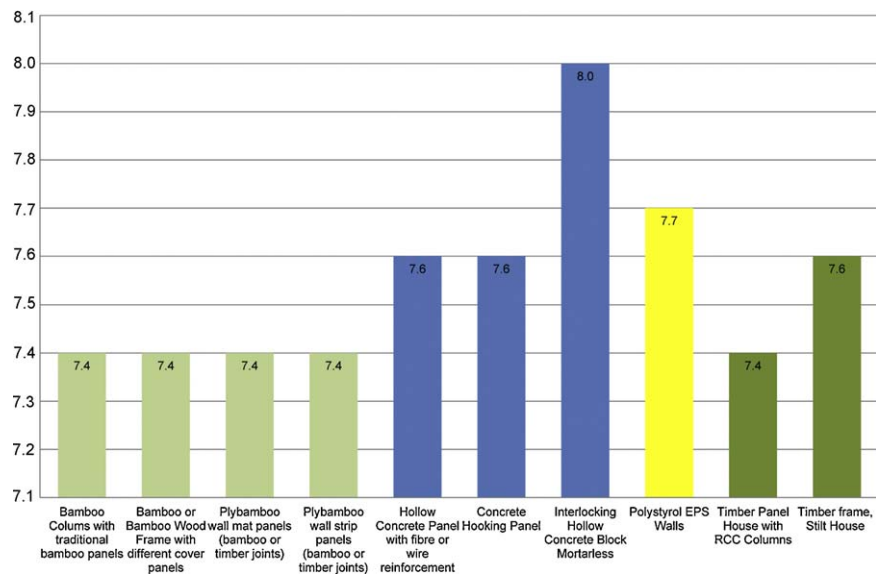


Fig. 4. Top technologies in the egalitarian and hierarchical weighting schemes.

3.3. Top technologies

Fig. 4 shows the top performing technologies under an egalitarian weighting schemes. It is possible to observe that these top technologies each achieved a score of 7.4 or higher in the assessment process. These technologies can be considered to be the most promising technologies, and their performances can certainly be improved with further research and development. As it was already identified in Section 3.1 the top scoring technologies belong to the categories bamboo, concrete, syntactical materials and timber. Having the interlocking hollow blocks technologies as the top ranking technology, closely followed by other concrete technologies.

To identify the strengths of these technologies, the results in each sustainability category are presented in the following sections. To represent the economic, environmental and societal aspects of

the concept of sustainability clusters of indicators were selected. In order to obtain comparable results, independently of the size of the indicator cluster, the final results were normalized into percentages.

3.4. Top technologies – economy

The assessment tool is divided into three main indicator clusters, economy, environment, and social. Each cluster is composed by different amount of indicators. Therefore, the results per cluster are presented in percentages related to the maximal score they could achieve per cluster. The top technologies were distributed in a range of 16% points and several technologies achieved equal scores. These two facts already show that a decision making process based only on one of the cluster will not provide conclusive results. For

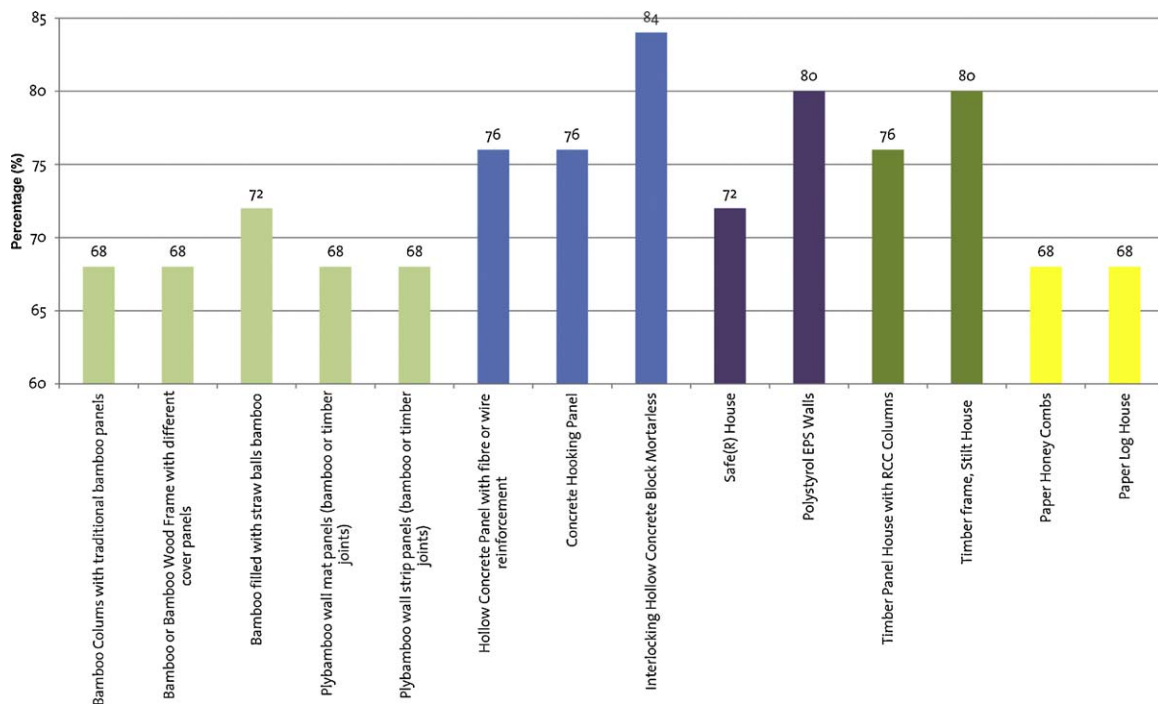


Fig. 5. Top technologies – economy.

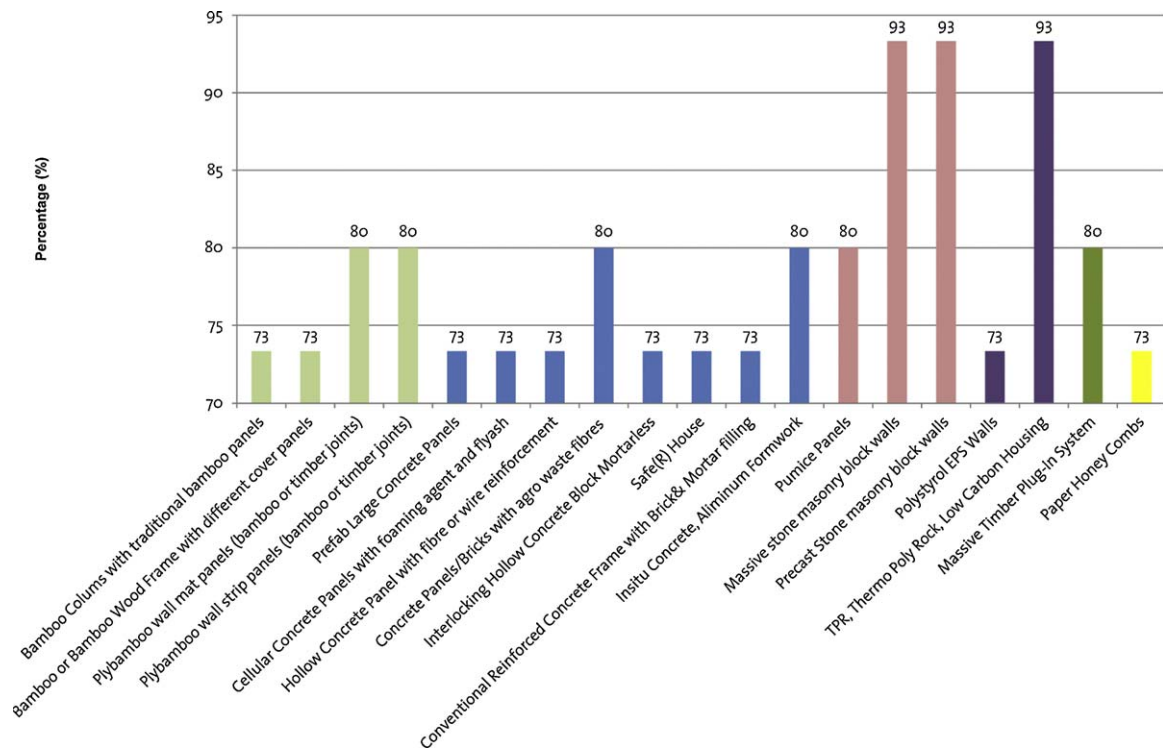


Fig. 6. Top construction technologies – environment.

the economy cluster the most influential indicators were the cost per square meter, the requirements of the building process, and the combined time schedule/degree of prefabrication. This shows that technologies that can be easily erected in short time, with a minimum investment are preferred, indicating that prefabricated and industrialized products will tend to perform better in this category (see Fig. 5).

3.5. Top construction technologies – environment

The results for the environment cluster have a range of 20% points and again several technologies achieved equal marks indifferently from the material category they belong to. Nineteen technologies were ranked as top for this cluster. This shows that technologies with promising environmental performance are

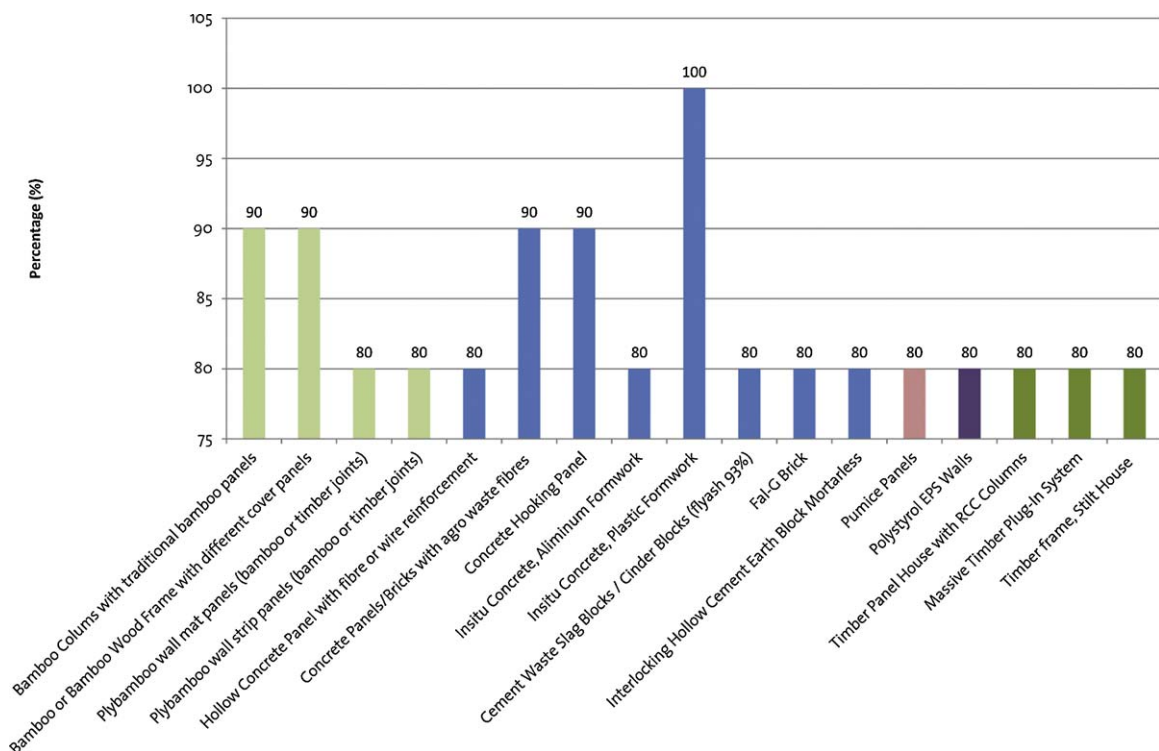


Fig. 7. Top technologies – society.

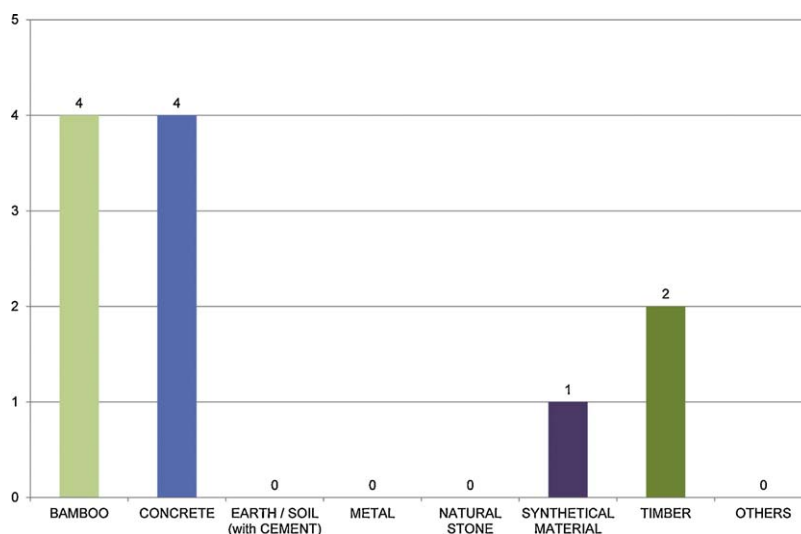


Fig. 8. Number of top ranking technologies by material category.

available in a good number. Nevertheless, a detailed life cycle assessment, where local factors like energy sources and transportation costs are considered, needs to be carried out in order to clearly identify the most promising technologies. The results also showed that the technologies achieving high scores on the indicators durability and/or recycling potential were selected as top technologies. Thus, showing the relevance of these indicators for the technologies' environmental performance (see Fig. 6).

3.6. Top technologies – society

The society cluster consists of two indicators. The top technologies on this cluster are distributed in a 20% point range. Seventeen technologies were ranked as top and all of them achieved high scores (see Fig. 7).

This shows that the available technologies have great potential for the creation of local value, either in terms of labour or materials. It is also clear that materials which are locally available or produced in situ will obtain higher scores given the proposed set of indicators.

The balance between environmental, social and economic factors is a key to the development of sustainable and affordable housing. Moreover, it is possible to consider the negative rebound effect for example obtaining increased durability by raising the price per square meter or to use industrialized technologies to reduce cost and increase efficiency but simultaneously reduce local value creation.

4. Discussion

This paper assessed construction technologies that will be able to sustainably provide shelter to low and lowest income communities in urban areas of emerging economies countries and have all already been used in practice. For the identification of promising technologies a set of 10 sustainability indicators have been developed based on a literature review and personal interviews. Furthermore criteria for grading from 0 to 10 with intermediate steps of 2 and linear ranking solutions were developed. In total 46 technologies have been assessed against the sample of sustainability indicators covering all material groups from bio-fibres to metals and from long term established to pilot phase constructions.

The findings showed that all material groups were represented in the top technologies; in many cases, these technologies enable the use of local materials. Socio-cultural and climatic condition

can also possibly be addressed by the top technologies because of their diversity. Generally, the level of information about these top technologies is high, making the evaluation reliable.

Improving the quality of the information in the database would certainly improve the validity of these results. In addition, some technologies are closely connected with regional programs and enjoy high levels of local acceptance despite having objective restrictions and drawbacks.

Fig. 8 shows that material's groups earth/soil; metal; natural stone; and others had no technologies ranked at the top. This is a clear indication that highly industrialized construction techniques (such as steel frames, polystyrene cladding, and metal panels from the "metal" category or paper honey combs and rapid prototyping from the "others" category) do not represent optimal solutions to the sustainable affordable housing problem given the current conditions and indicators.

The categories "timber" and "synthetic materials" show a very interesting trend. On one hand, timber products maintain its position as a prominent alternative technology despite claims of low environmental and social performance in many developing countries, but their performance can be improved with new models of production and certification. Moreover, education and research in timber construction have a very long tradition, making it an easily accessible technology with enough knowledge and regulatory support. On the other hand, synthetically produced materials are on the rise, and these new and innovative products present very interesting approaches to the challenges of sustainable affordable housing. However, there are serious concerns about their environmental performance and about the local value that they can produce in the long and short terms.

Finally, the two top-ranking material groups are to some extent inherently opposed, but each has undeniable strengths on its own. The case of concrete is very special, as many authors regard it as one of the most energy-demanding, carbon emission intensive and waste-producing construction materials; at the same time, its versatility is difficult to match. Beyond its well-known durability and mechanical strength, concrete can be easily mixed with other construction materials, it can be produced either at large industrial scales or at the local handcrafted level, and there is a long tradition of concrete construction education and research. These results show that there is a promising future for concrete in the sustainable affordable housing sector, although there remain areas for improvement, including the negative environmental impacts from cement production, the difficulty in dismantling and

recycling concrete structures, and the socio-economic implications associated with its production.

The “bamboo” group presents a totally different situation and challenges. One of the most important challenges is social acceptance; the association of bamboo with poverty has discouraged its introduction to the affordable housing sector. Moreover, knowledge of bamboo construction is not widespread, and bamboo construction is unregulated in most countries. Additionally, bamboo construction techniques are rarely taught in architectural or civil engineering faculties in bamboo-producing countries; thus, research into bamboo construction lags behind other construction techniques. Another challenge for bamboo is the lack of research and development of its mechanical properties and the possibilities for standardization. These two factors play a significant role in the quality and durability of the final buildings. Without them, bamboo construction techniques will be relegated to small-scale affordable housing programs. On the bright side, bamboo has a very strong environmental performance record that is coupled with the highest natural growth rate in the botanic world. It must be noted that bamboo grows naturally in the countries where the demand for housing is highest. It is clear that there are many opportunities for bamboo and that more research is needed into both its mechanical and construction properties and also its socio-economic aspects. Bamboo also offers interesting opportunities for rural and sub-urban communities to develop new business models and products to help solve the sustainable affordable housing crisis and to improve their livelihoods.

5. Sensitivity analysis

To assess the reliability of these results, a number of different weighting schemes were developed. In general, it was found that changes to the percentages allocated to each indicator or cluster of indicators resulted in minimal changes in the material category-level rankings and the overall performance. One weighting scheme was developed considering weighting economy by 55%, society by 30% and environment by 15%. This very significant variation in the allocated percentages, compared to the evenly distributed percentages used, only changed the rankings of four out of the ten top technologies.

Furthermore, all of the top-ranked technologies in both schemes (egalitarian and inverted hierarchical) presented improved performance in the economically oriented scheme. It is also important to note that even under the extreme condition of allocating 55% to the economy category, the material categories “steel” and “others” are still excluded from the top technologies, while the “bamboo” and “concrete” categories increased their representation under this weighting scheme.

6. Conclusions

After screening, assessing, and ranking 46 different construction technologies against 10 sustainability indicators, it is possible to conclude that the most promising technologies are closely connected to local production of materials. Under the proposed set of indicators and weighting factors, the most strongly performing technologies are those associated with either bio-based products (such as bamboo and timber) or with industrialized products (such as concrete or synthetic materials). This is a clear indication that there are opportunities underlying many technologies and that a deeper study of the top-ranking technologies is required.

Furthermore, the strengths of the top-ranking technologies can be associated with either their mechanical and environmental performance or with their socio-economic aspects. From the assessment process, it can be concluded that there is no perfect

solution to the sustainable affordable housing problem, but that combining multiple top-ranking technologies can provide an optimized solution. Considering that none of the top technologies achieved a maximum ranking in all the proposed indicators, it is possible to conclude that technologies should be strategically selected based on their relative strengths, which will result in the development of novel innovative materials and techniques in the affordable housing sector.

The results also showed that no technology achieved a grade higher than 8.0 out of 10, indicating that these technologies still have room for improvement. On one hand, the more traditional technologies need to be developed with the aim of achieving more standardized and flexible solutions within the framework of sustainable business models. On the other hand, the environmental and socio-economic performance of the more industrial solutions needs to be improved while maintaining their competitive presence in the market. Moreover, it is important to remark that the indicator system is far from perfect and the assessment process needs to be further developed aiming to reduce subjectivity and biased inputs.

Finally, having such a diverse range of top-ranking technologies demonstrates that there is enough technological variety available to tackle the challenges related to the varying local conditions of sustainable affordable housing projects. This variety also indicates the feasibility of combining technologies to alleviate affordable housing demand. Furthermore, it demonstrates that the most sustainable solutions for affordable housing projects are the solutions that maximize the potential of available construction materials and techniques. To demonstrate the feasibility of applying these technologies, it is necessary to develop studies that consider regional factors in depth. Furthermore, practical applications of these technologies will highlight the strengths and drawbacks of each technology. It is expected that further steps on this approach will help to validate the selected indicator and will identify new ones while simultaneously improving the reliability of the database.

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